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Research article

Analysis on the nitrogen drilling accident of Well Qionglai 1 (I): Major inducement events of the accident

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Abstract

Nitrogen drilling in poor tight gas sandstone should be safe because of very low gas production. But a serious accident of fire blowout occurred during nitrogen drilling of Well Qionglai 1. This is the first nitrogen drilling accident in China, which was beyond people's knowledge about the safety of nitrogen drilling and brought negative effects on the development of gas drilling technology still in start-up phase and resulted in dramatic reduction in application of gas drilling. In order to form a correct understanding, the accident was systematically analyzed, the major events resulting in this accident were inferred. It is discovered for the first time that violent ejection of rock clasts and natural gas occurred due to the sudden burst of downhole rock when the fractured tight gas zone was penetrated during nitrogen drilling, which has been named as "rock burst and blowout by gas bomb", short for "rock burst". Then all the induced events related to the rock burst are as following: upthrust force on drilling string from rock burst, bridging-off formed and destructed repeatedly at bit and centralizer, and so on. However, the most direct important event of the accident turns out to be the blockage in the blooie pipe from rock burst clasts and the resulted high pressure at the wellhead. The high pressure at the wellhead causes the blooie pipe to crack and trigged blowout and deflagration of natural gas, which is the direct presentation of the accident.

Keywords: Western Sichuan Basin; Well Qionglai 1; Fractures; Tight sandstone gas reservoir; Nitrogen drilling; Rock burst and blowout by gas bomb; Deflagration; Accident

1. Introduction

It is generally agreed in the world that nitrogen drilling is safe in tight gas reservoirs. According to the IADC classification criteria [1], this type of nitrogen drilling belongs to low risk operation, with comprehensive risk evaluation as "1B1" or "2B1", i.e., the risk level is 1 (no gas production) or 2 (low gas production), the application type is B (underbalanced drilling), and the fluid medium is 1 (nitrogen). Nitrogen drilling has been successfully applied in many wells in China. When drilled into a gas zone, there was a flare at outlet of blooie pipe meanwhile normal drilling was kept going on. In the process, no blowout or deflagration accident ever occurred [2]. However, a wild blowout fire suddenly occurred during nitrogen drilling in Well Qionglai 1 at 03:27 on 22 December, 2011, which was the first blowout fire accident occurred in nitrogen drilling in China. This accident had brought negative effects to the development of gas drilling technology that was still in

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start-up phase in China. As a result, the application of nitrogen drilling was largely reduced, and the intrinsic safety of this technology was even doubted [3]. Therefore, a correct and systematic understanding of this accident would not only prevent similar accidents from occurring once more, but also concern the spreading and development of gas drilling technology in the future.

Well Qionglai 1, targeting the Xujiahe Fm, is located in the Baimamiao structure of western Sichuan Basin. The third spud of 708–2200 m, from Penglaizhen Fm to Suining Fm, was designed to be drilled with nitrogen drilling and pneumatic hammer of $12^1/_4''$ bit to enhance ROP (Rate of Penetration). After the Shaximiao Formation was penetrated through to the depth of 200 m, the drilling would then be converted to mud drilling. The make-up of string was as follows: $12^1/_4''$ hammer bits + air hammers + double box subs + check valves + one 9″ non-magnetic drill collar + one 9″ drill collar + centralizer + one 9″ drill collar + joints + two 8" drill collars + joints + one $6^1/2''$ drill collar + 5″ drill pipes 662.31 m long + check valves + 5″ drill pipes.

The blooie pipe for gas drilling of the well was arranged as in Fig. 1, its configuration in order as below: a 9″ outlet on RCD (Rotary Control Device), a 9″ to 6″ bell joint connected to the 9″ outlet with its big end with flange, a 6″ T-joint connected to the small end of the 9″ to 6″ bell with the pin thread of the 6″ T-joint into the box thread of the 9″ to 6″ bell joint, a 6″ wired hose connected to the 6″ T-joint with the pin thread of the 6″ wired hose into the box thread of the 6″ T-joint, a 6″ to 9″ bell joint connected to the 6″ wired hose with its small end with flange, a 4 m long 9″ casing connected to the big end of the 6″ to 9″ bell joint with flange, a 9″ T-joint with a cecum-end made a right turn on the blooie pipe, another 9″ T-joint with a cecum-end made another right turn after 42 m long 9″ casing, 35 m long 9″ casing extended to the flare pit.

Based on check computation and numerical simulation, the blooie pipe was proved to be able to meet both the requirement of normal gas drilling to enhance ROP in terms of cuttings carrying and pressure resistance and the requirements of further drilling under 300×10^3 m^3/d gas production circumstances; even if the gas production reached 1×10^6 m^3/d, and further drilling after the gas zone penetrated could not be conducted due to the failure of cuttings carrying from the wellbore, blockage and burst should not occur in the blow-off of produced gas from the blooie pipe.

The designed technological parameters for gas drilling of the well were as follows: $12^1/_4''$ bit of air hammer drilling, 120 m^3/min gas injection rate, 30 kN weight-on-bit and 35 r/min rotation rate. The air drilling to enhance ROP commenced at 724 m in the well; when the well was drilled to the depth of 980.84 m (Penglaizhen Fm), the total hydrocarbon rose from 0 to 4%, unchanged, and air drilling was converted to nitrogen drilling. When the well was drilled to the depth of 1003.1 m using nitrogen drilling, the total hydrocarbon rose to 40%, ignition at the outlet of the blooie pipe was successful, and the flame was 7–8 m high; simultaneously, the standpipe pressure rose from 1.4 MPa to 7.6 MPa, and one of the nozzles of air hammer bit was discovered to have been plugged after POOH. After cleaning of the nozzle, RIH, nitrogen drilling was continued, and the total hydrocarbon centered around 4% all along till the Shaximiao Fm (the depth of top boundary is at 2000 m) was drilled. The stratigraphic prediction of the drilled intervals basically tallied with the drilling results.

Before the accident, the oxygen content in nitrogen drilling was controlled below 5%, the standpipe pressure was about 2 MPa, the drill time was 4–5 min/m, the weight on hook (WOH), torque and cuttings cleaning were all normal, and the bottomhole pressure (BHP) was calculated as 0.36 MPa, the drilling was kept going on smoothly in this situation to 2144.23 m depth. The accident occurred at the well depth of 2144.23 m in Shaximiao Fm.

2. Interview record regarding the accident

The primary evidences collected by inquiring the personnel on duty at the time of accident are presented chronologically as follows:

Drilling was normal and no any anomaly was observed at 03:27 on 22 December, 2011. Suddenly, a clash sound

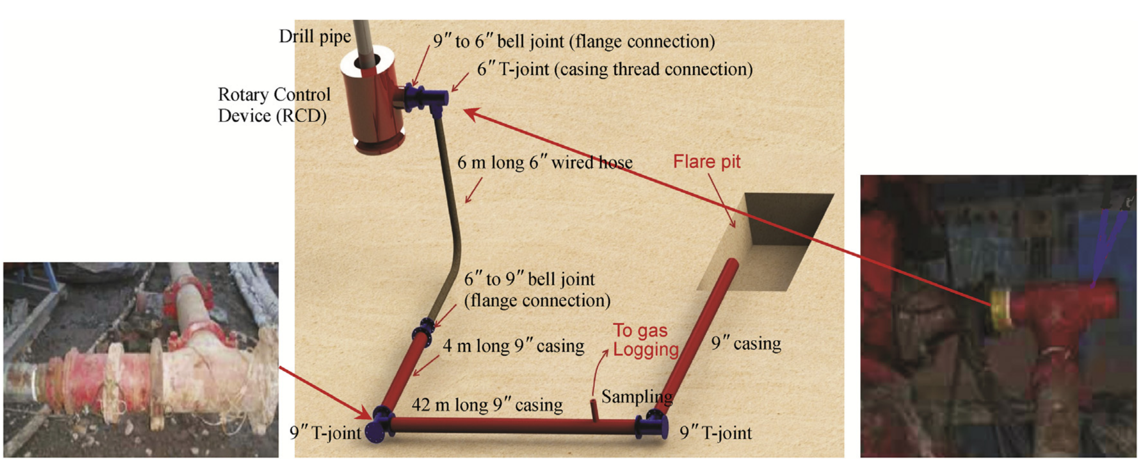


Fig. 1. The blooie pipe for gas drilling in Well Qionglai 1.

between the swivel and the hook was heard, and the deflexion of kelly, the rotational swing of traveling block and swivel and the violent swing of weight indicator pointer were observed. The driller started to stop drilling and tried to lift the drilling string. Another clash was heard before long. Then piercing sound was heard at wellsite, and dust pervaded below the drill floor. The air compressor operator started emergency shutdown. A dull blare was heard a few seconds later (the time for a logger to run more than 20 m), the driller stopped the rotary table. The wellhead and drill floor caught fire immediately, and the flame spread all around. The remote console for well control was in flame and could not be operated. The driller stopped hoisting, all personnel implemented emergency evacuation, and time elapsed for only about more than 1 min. At 03:43, the derrick was burnt down and fell in the front of the wellsite. At 10:20 the next day, well killing was successfully performed using 158 m^3 kill fluids with 1.6 g/cm^3 density.

3. Post-accident investigation data

Close investigation was conducted after the accident, and primary evidences were obtained as follows:

3.1. No piercement and no failure in sealing on stripper rubber of RCD

The subtense distance of a new stripper rubber ranges between 96 and 98 mm, and the rated sealing pressure of it is 10.5 MPa. After the accident occurred, the stripper rubber used at the wellsite was measured, showing that the subtense distance became 122 mm, and deformation, wearing and plastic deformation at high temperature existed; however, the subtense distance of kelly is 133 mm. Therefore, the stripper rubber can maintain sealing with the help of self sealing effect of it at high pressure. As shown by field investigation photo in Fig. 2, there is no piercement on the stripper rubber.

Fig. 2. A basically perfect stripper rubber.

3.2. Falling of the 6″T-joint connecting the wired hose off the bell joint of RCD

As shown by the field investigation photo in Fig. 3, the **6″** T-joint fell off the casing thread connecting the 9″ to 6″ bell joint of RCD, and the thread had asymmetric deformation, but was basically perfect, showing an elastic slip.

Fig. 3. Slip and asymmetric deformation on the pin thread of the 6″ T-joint.

3.3. Complete break and falling of the wired hose off the 6″ T-joint, characterized by an apparent fatigue failure at the fracture

As shown by the field investigation photos in Fig. 4a and b, the 6″ wired hose had completely separated from the connected 6″ T-joint, with fracture exhibiting two stages of apparent destruction characteristics: the wires destructed at the first stage occupy a 3/4 annular area at both front and rear sides of the inlet section of the wired hose (facing the outlet section of the RCD, the right hand side is the front side), with rear side being smaller, mostly exhibiting relatively regular fractures, without stretch elongation; they belong to fatigue fractures or external force brittle tensile failures.

The wires destructed at the second stage occupy a 1/4 annular area at both left side and right side of the inlet section of the wired hose, with left side (the side close to the wellhead) being smaller; the remaining wires exhibit apparent plastic stretch elongation, pinpoint shape at tip, belonging to a plastic elongated fracture in a combustion environment.

a. The 6″ T-joint falling off the bell jiont

b. The wired hose fractured from the 6″ T-joint

c. The directions of the wired hose

Fig. 4. Field investigation photos of broken of the wired hose.

3.4. Blowing of substantial rock dust coming from the Shaximiao Fm out of the outlet of the RCD, and its accumulation below the drill floor

A great deal of clasts and dust were accumulated below the drill floor. As shown by the field investigation photos in Figs. 5 and 6, there is no obvious dust accumulation both on the top of the RCD and in the groove on the top, whereas on the top of ball BOP (back to fire-fighting lance), there are a great deal of dust and sand particle accumulations. This phenomenon shows that the sealing of the stripper rubber in the RCD was perfect in the course of the accident, and the clasts and dust should have blown out of the side outlet of the RCD.

The clasts blown out of the hole are dust-sized to centimeter-sized, which was proved by lithic constituent analysis to come from the Shaximiao Fm (Fig. 7).

3.5. Eroded perforation on the 6″ T-joint connecting the wired hose

As shown by the field investigation photo in Fig. 8 and the data obtained from the pachometer, there is severe erosion on the 6″ T-joint, e.g., there is an oval perforation with major and minor axis of 1.5 cm and 1 cm respectively, whose edge was everted slightly.

3.6. Special downhole anomaly shown by log data in the accident process

The 2 s interval log data in the accident process shown special downhole anomaly, especially the change in WOH (weight on hook) and WOB (weight-on-bit). As shown in Fig. 9, in the course of normal drilling before the accident, the WOH and the WOB were stabilized at about 770 kN and 30 kN, respectively. Suddenly, the WOH dropped below 30 kN, and the WOB dropped to zero. About 21 s later, the WOH and the WOB suddenly jumped to 300 kN and 500 kN,

Fig. 5. Accumulation of dust on the top of BOP.

Fig. 6. No dust accumulation on the top of RCD.

a. Rock particles (Size: >80 mesh) b. Rock dust (Size: < 80 mesh)

Fig. 7. Rock particles and dust blown out of a wellbore.

respectively. Another 18 s later, the WOH suddenly jumped to 450 kN, and the WOB suddenly dropped to 400 kN. Another 10s later, the WOB suddenly dropped to zero, whereas the WOH rose continuously, and gradually approached the normal weight on hook of the drill string.

4. Speculation about important events resulting in the accident

It was discovered based on the interview, investigation and log data of the accident process that the nitrogen drilling accident of Well Qionglai 1 is a superposition of emergent chain events. It was triggered by a root event, then, a series of inducing events were generated, and finally, the fatal deflagration fire accident was formed. What the hell is the root event triggering the accident? Because the accident occurred during drilling in Shaximiao Fm, a tight gas sandstone formation, so the root event should be hidden in the drilling of tight gas sandstones.

4.1. Speculation about "rock burst" phenomenon

As shown in Fig. 10, if moderate high permeability sandstone gas zone is targeted by nitrogen drilling, when the gas zone is drilled in, natural gas flows out immediately; afterwards, as the drilling goes on, the gas flow rate rises in proportion; after the whole gas zone has been drilled out, the gas flow rate would become relatively stable.

However, it is quite a different case in drilling tight sandstone gas zone similar to Shaximiao Fm. There was no gas produced from drilling before the accident. At depth of 2144.23 m vast natural gas and rock chips and powders spouted suddenly from the well. The Shaximiao Fm belongs to typical tight sandstone dry gas reservoir [4], with depth ranging between 2000 and 2650 m and formation pore pressure coefficient of 1.3–1.4 proved by drilling. Because the permeability is very low in the matrix, if no fracture is encountered, such tight sandstone formation basically does not have commercial productivity; it has been proved by the drilled wells that there is no commercial productivity in the Shaximiao Fm (the best show of this Formation in adjacent wells are: maximum daily gas flow rate of 4900 m^3 at DST and 5200 m^3 after fracturing).

For the tight gas zone like Shaximiao Fm, if there is no fracture, affected by very low permeability of porous matrix [4] and compaction effect around the wellbore of gas drilling [5], gas basically does not flow out of the formation drilled in, (or only trace gas is shown, depending on the thickness and permeability of formation drilled in). If there is a fracture as shown in Fig 11 (although it is generally believed that fracture

Fig. 8. Piercement and erosion of the 6″ T-joint.

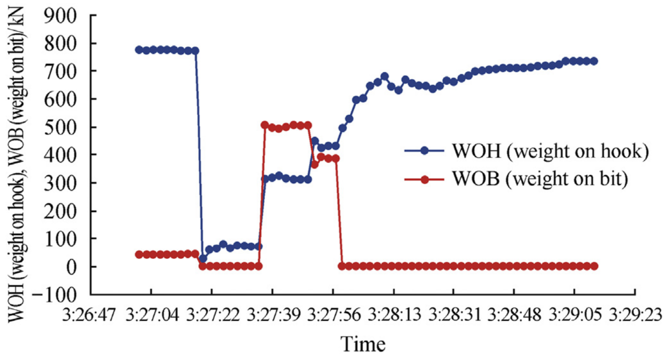


Fig. 9. Log data in the accident process.

is underdeveloped in the formation, fracture possibly exists in local area), the pressure in the fracture is the formation pore pressure (about 30 MPa), while the pressure in the wellbore is only 0.36 MPa. When there is certain distance between the fracture and the bottomhole, due to the very low permeability of rock wall between the fracture and the bottomhole, the high pressure gas in the fracture would not decompress through the rock wall, and high pressure is still trapped in the fracture (initial formation pressure). However, when the bottomhole is close enough to the fracture, the strength of the rock wall between the fracture and the bottomhole is insufficient to resist the destructive force formed by high differential pressure, the rock wall instantly bursts apart, breaks up, and a great deal of sloughing clasts and released high pressure gas spray into the wellbore. This phenomenon is temporarily denominated as "rock burst" phenomenon of gas drilling in the paper.

The amount of rock burst-sloughing matter depends on the factors like differential pressure, rock strength and fracture geometry; the rock burst-sloughing matter in high angle fracture should be more than that in low angle fracture, and big

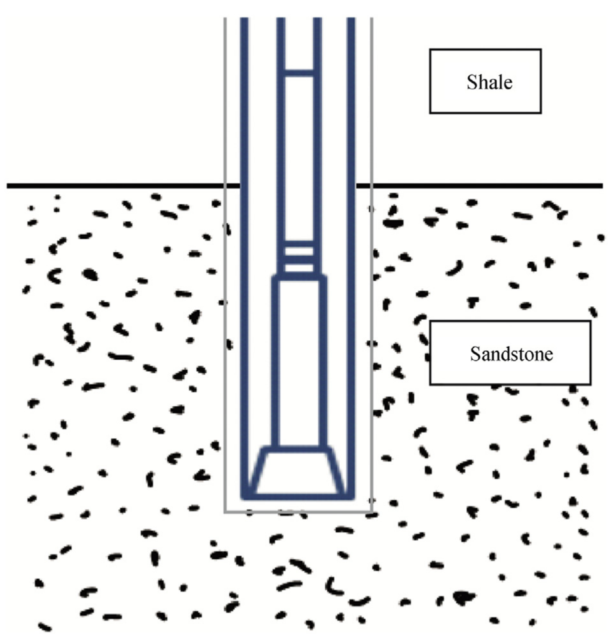


Fig. 10. Nitrogen drilling in a good sandstone gas zone.

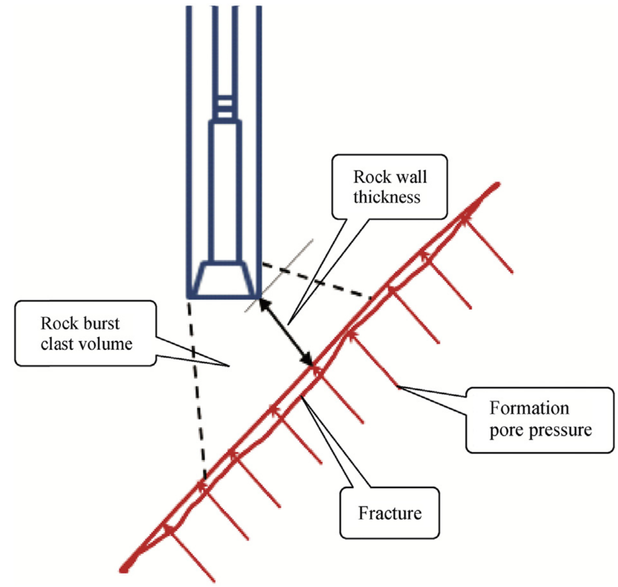


Fig. 11. Sketch map of destruction by "rock burst".

hole results in more rock burst clast volume. The computation of rock burst shattering process is relatively complicated; with reference to the gross hypothesis of "blasting crater" [6] shown in Fig. 11, the tensile strength of Shaximiao Fm sandstone ranges between 1 and 2 MPa, the thickness of rock wall between the fracture and the bottomhole at the time of rock burst is roughly estimated to be less than 0.5 m, and the clast volume resulted from rock burst is about 1 m^3 (the cone volume can be estimated by regarding the shattered body as an approximate frustum of a cone, with top diameter of 1.5–2 times wellbore diameter, conical frustum height equaling the rock wall thickness and cone apex angle ranging between 30° and 45°). The time for the occurrence of rock burst should be within hundreds of milliseconds; furthermore, the larger the differential pressure and the higher the rock strength, the shorter the rock burst time would be.

Such phenomenon of "sudden burst of rock and violent ejection together with natural gas" in gas drilling has never been reported in the literature, monographs and engineering records related to gas drilling both at home and abroad, and this should be a discovery for the first time. It is similar to the "rock burst" and "outburst" in mine exploitation, but it is greatly different.

The term of "rock burst" has existed in underground tunneling like mining and subterranean crossing for a long time, referring to a kind of very complicated sudden dynamic breaking of rock body occurred in the course of manual excavation [6]. Within the rock mechanics discipline system of underground engineering domain, the "sudden dynamic breaking of rock body" not only is a worldwide common problem, but also has not been unified in term of its academic name and specialized vocabulary.

Rock burst universally exists in the underground excavation fields like non-coal mining, subterranean crossing, dam engineering and underground engineering; therefore, the terminology of "rock burst" has been widely applied, and refers to the phenomenon that "the elastic deformation potential accumulated in the underground rock mass due to the stress concentration is suddenly released under certain conditions, and causes the rock to instantly burst and eject clasts, simultaneously, accompanied by some degree of sound and quake". Slight rock burst only results in locally sloughed particles or fragments, free of ejection; whereas in severe rock burst, several tons of rock would instantly burst, with rock particles and fragments being ejected to tens of meters away, and simultaneously accompanied by sound and quake. Such type of rock burst usually occurs in hard brittle rock mass. The elastic deformation energy accumulated in rock mass usually comes from two aspects: firstly, the elastic deformation energy accumulated and preserved in the course of tectonic deformation of underground rock, which is mostly related to violent tectonic stress; secondly, local stress concentration resulted from redistribution of stress of underground rock after manual excavation, which not only is related to original tectonic stress, but also to the shape and depth of tunneling; when other conditions are same, the deeper the tunnel, the easier the rock burst occurs, e.g., severe rock burst frequently occurs in deep pits excavated, such as in gold mine of South Africa.

In coal mine field, rock burst universally exists. Its scale is larger, and several to tens of tons of coal rock burst are often seen. The "rock burst" occurred in coal mine field is usually termed "outburst". "Coal and gas outburst" generally refers to the phenomenon that "the elastic deformation potential accumulated in coal is suddenly released under certain conditions, and causes substantial coal and gas to instantly erupt, simultaneously, accompanied by big sound and quake". The "outburst" in coal mine field can be divided into two types by inducement: mechanical inducement and gas inducement. The "coal burst" of mechanical inducement is also called "bump" (percussive ground pressure, pressure bump, pressure shock, etc.). With occurrence mechanism similar to that of aforesaid rock burst, it mostly occurs under circumstances of hard coal and high tectonic stress. However, because the strength of coal is relatively low and the joints are more developed, the shattered volume resulted from rock burst is larger, and the rock burst scale is larger. In the course of shattering and eruption of coal, some adsorbed methane is desorbed. Therefore, the eruptive material is a mixture of coal and gas. The outburst of gas inducement is termed "gas outburst, gas burst", and its mechanism is complicated and disputable. A typical mechanism interpretation is the "gas pocket" theory: in the area where tectonic stress is concentrated, the coal is structurally shattered and "pulverized coal pocket" is formed, which is saturated by methane in adsorbed state; under buried state, the methane in the pulverized coal pocket is in a stable adsorbed state at high pressure; in the course of pit excavation, when the working face is close to the pulverized coal pocket, due to the excavation unloading effect, the joints are opened, the permeability of coal is increased, and the low pressure in the pit is transferred to the pulverized coal pocket, where the pressure is reduced; when the pressure in the pulverized coal pocket is reduced below the methane desorption pressure, the methane in adsorbed state is quickly released to free state; it causes the gas in free state in the pulverized coal pocket to sharply increase, resulting a sharp rise of pressure; as a result, the coal wall between the pulverized coal pocket and the working face is burst, and substantial coal and methane gas are instantly ejected.

"Mine earthquake" is a term closely related to rock burst, and generally refers to a mining induced earthquake that can be felt on the ground of a mining area. The rock burst, bump and gas outburst are all accompanied by earthquake; when the earthquake is large enough to be felt on the ground, it forms mine earthquake. Another mine earthquake results from the local formation slippage triggered by the change in regional crustal stress in mining, and such mine earthquake does not have direct contact with the rock burst in the pits.

Obviously, although such phenomenon as "sudden burst of rock and violent ejection together with natural gas" occurred in gas drilling is also a "sudden dynamic breaking of a rock body", its inducement and manifestation are quite different from any rock burst or outburst occurred in underground engineering like mining and coal cutting. The rock burst in non-coal underground engineering mostly occurs under circumstances of hard rock and high tectonic stress, its inducement lies in "sudden release of accumulated elastic energy", and its phenomenon is that the shattered rock mass is ejected all at once and not accompanied by gas. The inducement of bump in coal mine also lies in "sudden release of accumulated elastic energy", but its phenomenon is that the shattered rock mass is ejected all at once and accompanied by the desorption of adsorbed gas simultaneously, as a result, in such a case, one ton of outburst coal is generally accompanied by several to tens of cubic meters methane gas. The inducement of gas outburst in coal mine lies in "high pressure gas in free state formed by rapid desorption of methane adsorbed in gas pocket", and the phenomenon is that the coal is shattered by high pressure gas and then ejection occurs all at once, therefore, in such a case, one ton of outburst coal is generally accompanied by more methane gas than a coal bump. The rock burst, bump and gas outburst all take place at a depth of about dozens of to a hundred meters underground, and in a big space like tunnels. Furthermore, they all exhibit as one-time-ejection-and-then-at-rest mixture of rock and rock gas.

However, the phenomenon of "sudden burst of rock and violent ejection together with natural gas" in gas drilling occurs in deep zones of thousands of meters and in a small hole, with inducement being that "the great differential pressure between the high pressure natural gas in the fracture of tight sandstone and the low pressure gas in the wellbore makes the rock wall between the fracture and the bottomhole burst". This phenomenon is more like a gas cannon "firing shell via cannon bore from huge high pressure gas container", but it is rock fragments instead of shell fired. The rock-shattered volume involved in eruption is small (smaller than 1 m^3 rock volume), but the subsequent high pressure gas would ceaselessly be ejected. The ejection of natural gas is also divided into several stages: (1) the free natural gas compressed at high pressure in the fracture is violently ejected together with the shattered clasts in a very short period of time; (2) the porous matrix around the fracture supplies gas to the fracture, then injects the wellbore, and the blowout momentum of natural gas is largely slackened; and (3) a wide range of matrix supplies gas to the fracture in a filtration mode, and the blowout is stabilized.

What terminology on earth is used to describe this phenomenon in gas drilling? If it is simply termed “rock burst”, it is hard to reflect the specific mechanism and feature of this phenomenon. Based on the characteristic description of the phenomenon that: “in the course of gas drilling, the high pressure natural gas in the fracture of tight sandstone reservoir triggers burst and shattering of rock at bottomhole and simultaneous ejection together along the wellbore, and then the high pressure natural gas in the reservoir continually injects the wellbore”. For the sake of highlighting the characteristic of the phenomenon that “rock fragment and high pressure natural gas are violently ejected like shell firing”, such phenomenon as “rock suddenly bursts and is violently ejected together with natural gas” should be called “rock burst and blowout by gas bomb”. Considering the inconvenient application of the terminology due to its overlength, we refer it as “rock burst in gas drilling” or “rock bomb in gas drilling”, for short as “rock burst” or “rock bomb”.

4.2. Speculation about “bridging-off”

As shown in Fig. 12, when a great deal of clasts move upward at high speed, substantial particles of various sizes arrive at the place where the flow channel suddenly narrows (where bit, centralizer, etc.) also at high speed and bridge rapidly, loose sand bridges would be formed, which could result in the occurrence of sand bridge sticking phenomenon. If the flow channel at blocking point suddenly unblocked (e.g., continually lifting of drilling string), such loose sand bridges formed instantly could be destroyed, and the clasts would go on to move upward; if the flow channel at blocking point is not unblocked all along (e.g., motionless of flat bottomed hammer bit of air hammer, full packed centralizer of small flow channel, balled bit or centralizer), the flow barrier at blocking point would slow the gas below the sand bridge, the bulky grains would settle, whereas the small particles and dust would go on moving upward; as a result, on the basis of bridging of bulky grains, the small particles would further fill, the dust would further be compacted, the particle accumulation changes from loose state to tight state, and tight and impermeable fixed bridging-off is formed ultimately [7]. The tight bridging-off separates the wellbore into two different pressure spaces: below it is the high pressure of formation pore pressure (30 MPa), and above it is the low pressure of still nitrogen column weight (0.12 MPa). In Well Qionglai 1, the rock burst firstly forms the fixed bridging-off at the bit (called the first bridging-off).

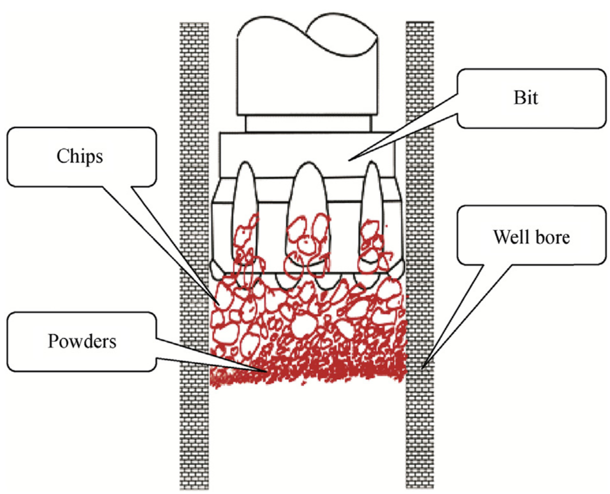


Fig. 12. The first bridging-off.

4.3. Speculation about “rock burst upthrust”

In the first moment of rock burst, the energy compressed by high pressure gas in the fracture system is mainly transformed into elastic deformation energy of rock; the tremendous elastic deformation energy of rock causes some rocks to be broken into particles which are then ejected, whose initial velocity would exceed acoustic velocity or even reach the initial velocity of rifle bullet [8]. These ejected clastic particles directly impact the bit, and the momentum of the particle swarm is converted into the thrust instantly acted on the bit. This is the initial upthrust of rock burst.

If the ejected clasts of rock burst do not form bridging-off at the bit, the subsequent high pressure gas flow would carry the sloughed clasts of rock burst to continue to flow through the bit, and the impact force of the high velocity gas and solid two-phase flow on the bit is no other than the subsequent upthrust of rock burst (dynamic upthrust), which directly acts on the bit; with the release of high pressure gas and the expulsion of clasts, the transient gas and solid two-phase flow is converted into steady single-phase gas flow, the subsequent upthrust of rock burst reduces or even disappears. The upthrust of rock burst speculated under such conditions is shown in Fig. 13a.

If the ejected clasts of rock burst have formed bridging-off at the bit, the subsequent upthrust of rock burst is no other than the upthrust of sand bridge (static upthrust), the sum of the static upthrust acted on the bit and the self-locking force of sand bridge equals the force of high pressure gas below the sand bridge acted on the sand bridge, and the upthrust of rock burst speculated under such conditions is shown in Fig. 13b. Under the action of upthrust, the drill string could be compressed and deformed and becomes helical buckling.

4.4. Speculation about “destruction and recreation of bridging-off”

Bridging-off at the bit would suddenly destruct under the rotation of drill string, and the compression energy of high pressure gas below the sand bridge is instantly transformed into the kinetic energy of sand bridge particles; because its principle is similar to the working process of “gas cannon” [9] (e.g., one stage gas cannon can allow the 1 mm steel shot to

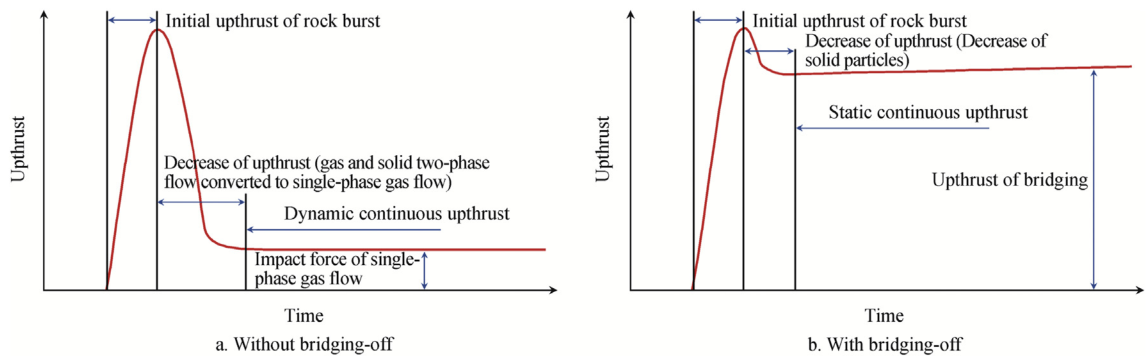


Fig. 13. Speculation about the change in rock burst upthrust with time.

generate a more than 800 m/s initial velocity in a Ø10 mm × 12 m long launching tube at 10 MPa pressure), this phenomenon is called "gas cannon effect". Under the action of "gas cannon effect", the sand bridge particles are ejected upward at a very high speed, accompanied by drill pipe release simultaneously (instant release of torsional deformation, exhibiting a sudden jump of rotation rate; sudden release of compression deformation of drill pipe, exhibiting a sudden downrush of bit).

The clasts ejected upward arrive at the centralizer instantly, and forms bridging-off once more due to the narrowing of flow channel, which is called the second bridging-off, resulting in second upthrust of drill string which is stuck once more (exhibiting sudden drop of rotation rate), as shown in Fig. 14. Moreover, below the bridging-off is still the high pressure (30 MPa) still natural gas, and above it is still the low pressure (0.12 MPa) still nitrogen; a great deal of rock burst clasts above and below the bit settle due to its deadweight, and form loose accumulation.

Under the rotation of drill string, the bridging-off at the centralizer (the second bridging-off) suddenly destructs, resulting in a "gas cannon" effect; the sand bridge particles are ejected upward at a very high speed, accompanied by drill pipe release simultaneously (instant release of torsional deformation, exhibiting a sudden jump of rotation rate; sudden release of compression deformation of drill pipe, downrush of bit).

The sloughed particles below the centralizer move upward under the push and drag of gas flow, as the centralizer moving downwards and the particles under the centralizer moving upwards, a self-locking effect around the centralizer will happen by the particles between the centralizer and the well-wall as shown as in Fig 15a and the drill pipe will be stuck again, and form bridging-off once more, which is called the third bridging-off, as shown in Fig. 16. The drill string is stuck once more (exhibiting a sudden drop of rotation rate), at this time, below the bridging-off is still high pressure (30 MPa), and above it is still low pressure (0.12 MPa).

If the drill string kept to be rotated and pulled up, the third bridging-off on the centralizer will be destroyed suddenly, most particles in the sand bridge will be shot up with a tremendous velocity by the gas cannon effect of the high pressured natural gas under the bridging-off. As the centralizer moving upwards by pulling up and the particles under the

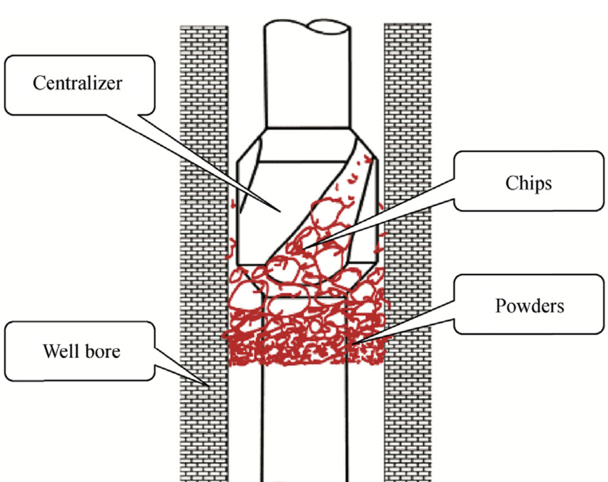


Fig. 14. The second bridging-off.

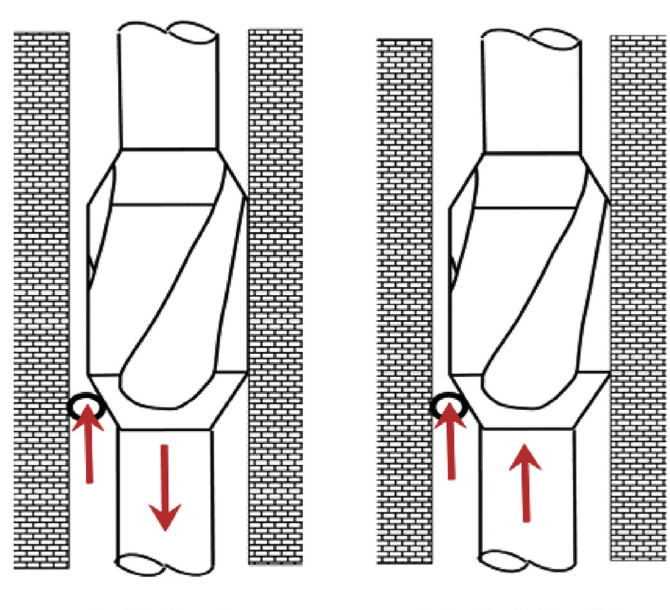


Fig. 15. Self-locking and unlocking of a drill string moved down and up.

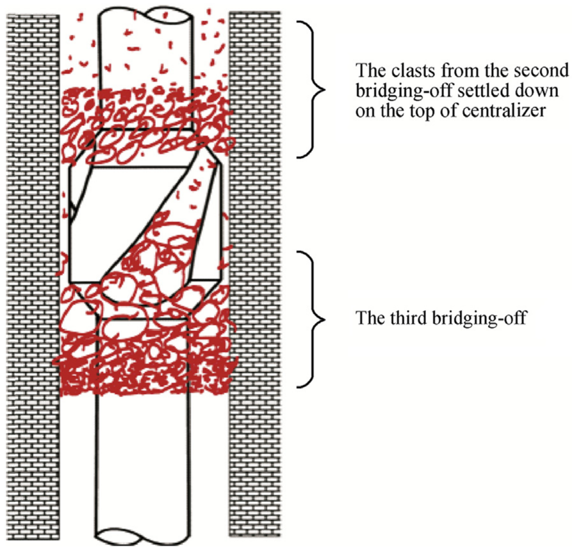


Fig. 16. The third bridging-off.

centralizer moving upwards by flowing, a self-unlocking effect will continuously happen between the upwards moving centralizer and the upwards moving particles as shown as in Fig 15b and the drill pipe will move up continuously, no new bridging-off can be formed here.

4.5. Speculation about "motion law of sand bridge clasts after bridging-off destruction"

At every moment when the bridging-off is destructed, the "gas cannon" effect makes the compression energy of high pressure gas below the sand bridge be transformed into the kinetic energy of sand bridge clast. As a result, sand bridge clasts are ejected upward at a very high initial velocity (exceeding acoustic velocity, or even reaching the bullet speed), and simultaneously, very few high pressure gas below the sand bridge expands and enters the wellbore above it.

The motion law of sand bridge clasts after bridging-off destruction can be divided into three cases.

Firstly, after the sand bridge at a place has been destructed, sand bridge clasts are ejected upward at a high speed, and arrives at another narrowing point of the flow channel, and forms a new bridging-off once more. A case in point is in the accident of Well Qionglai 1, after the first bridging-off (as shown in Fig. 12) was destructed, the second bridging-off (at centralizer) was formed, as shown in Fig. 14.

Secondly, after the sand bridge at a place has been destructed, sand bridge clasts are ejected upward at a high speed, however, bridging-off is formed once more at the place before long by the subsequent movement particles; by nature, after the sand bridge has been destructed, the high pressure gas below the sand bridge expands and pushes the still gas above the sand bridge to be compressed and flow, however, the bridging-off is formed once more before the flow of the gas above the sand bridge, as a result, the gas above the sand bridge continues to be still. In the accident of Well Qionglai 1, the second bridging-off destruction and the third bridging-off formation are no other than such a case, as shown in Fig. 16. After the second bridging-off was destructed, although clasts at the centralizer were ejected upward into the wellbore at a very high speed, because the gas above the centralizer in the wellbore was still, these particles, decelerated rapidly due to the impedance of gas and the collision of sidewall, started to fall after having moved upward for about hundreds of meters (when a certain mass of particle is ejected upward at a given initial velocity, its ejection altitude depends on the impedance of gas, whereas the computation for the impedance of gas to a supersonic velocity particle is awfully complicated [10]. The data available for reference come from the rock blasting engineering, showing that the ejection altitude of millimeters-sized particles can reach hundreds of to about one thousand meters [8]), and the falling particles settled on the top of the centralizer and formed loose accumulation.

Thirdly, after the sand bridge at a place has been destructed, sand bridge clasts are ejected upward at a high speed, afterwards, no new bridging-off is formed in the annulus, and the whole annulus starts to be unblocked. The low pressure area above the sand bridge is connected with the high pressure area below it; the high pressure compressed natural gas (yellow in the figure) below the sand bridge starts to expand, and pushes the low pressure nitrogen (green in the figure) above it to be compressed and flow; the natural gas continuously pushes the nitrogen above it to flow in a slug mode, then, the gas in the whole annulus starts to be in a flow state, and the flow rate gradually speeds up. The lithoclast moving upward in the annulus is divided into two parts. The first part is composed of sand bridge clasts formed at the time of sand bridge destruction and the particles settled on the top of the sand bridge (called the? first stream of clasts). These particles have obtained very high initial velocity (exceeding acoustic velocity) at a sudden collapse of the sand bridge. This initial velocity makes these particles rise by hundreds of meters instantly and enter the still nitrogen annulus interval. Afterwards, the flow of gas in the whole wellbore carries these particles to go on moving upward, as shown in Fig. 17b. The second part is the loose permeable particles naturally accumulated by gravity. The high pressure natural gas passes them and forms decompression flow. However, when the flow rate is large enough to form greater dynamic differential pressure, the loosely accumulated particles are carried away layer by layer (similar to the conversion from particle-fixed bed to fluid bed [11]). These particles do not have very high initial velocity, and mainly move upward carried by the expansion flow of natural gas, which is called the second stream of clasts, as shown in Fig. 17c. Therefore, the distance between the first stream of clasts and the second stream of clasts is hundreds of meters away.

When the high-concentration solid particle slug formed after sand bridge destruction moves upward, the different initial velocity, inertia force and resistance of the solid particles resulted from their different sizes make the entire particle slug start to disperse and extend, and the solid concentration drops. Simultaneously, the high speed impact among particles themselves and between particles and the sidewall make the particles be further shattered, the large-sized particles reduce, and the small-sized particles increase. Therefore, when the

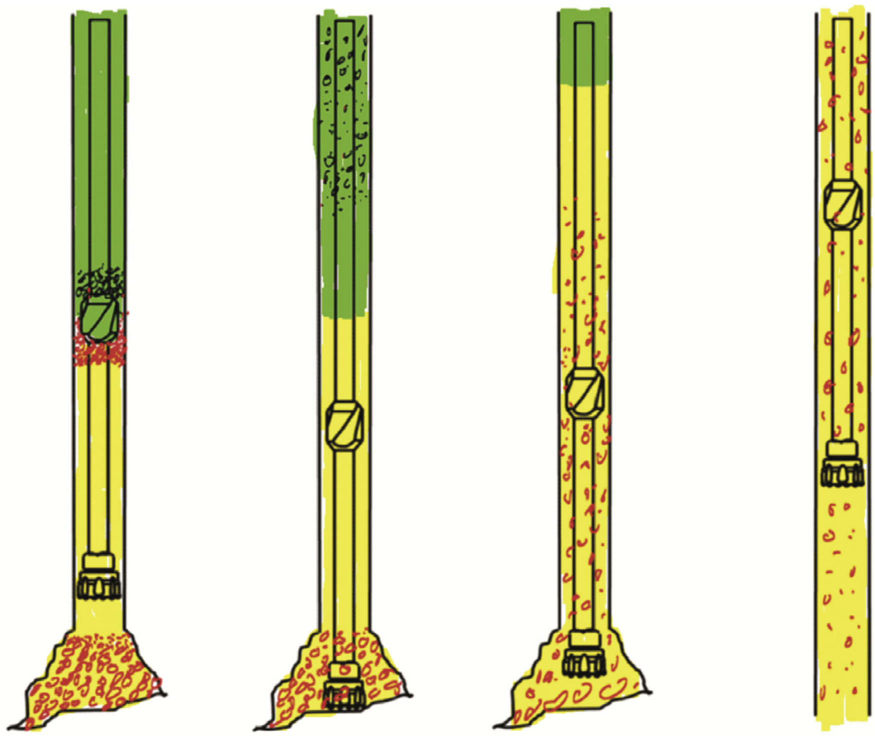


Fig. 17. First and second stream of clasts (Green-Nitrogen, Yellow-Gas).

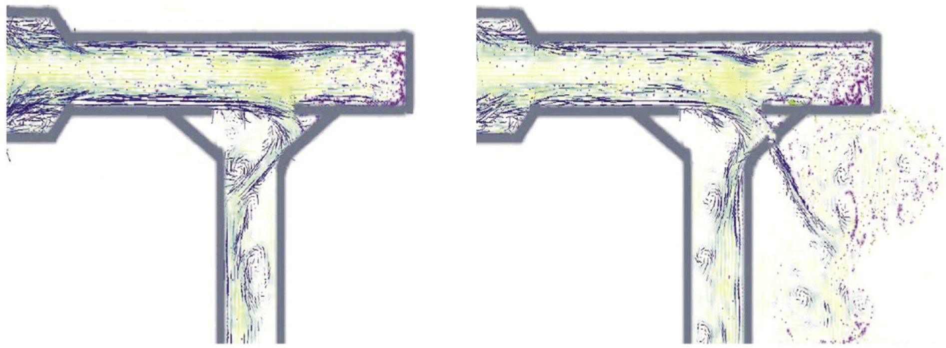
high-concentration solid particle slug containing lots of concentrated bulky grains in the lower interval moves upward into the upper interval, it becomes a longer low-concentration solid particle slug containing fewer dispersed bulky grains, as shown in Fig. 17d.

4.6. Speculation about "erosion and piercement of the 6″ T-joint"

According to the gas and solid two-phase flow theory, when the flow field direction suddenly changes, the solid particle cannot in time change its direction following the gas flow, but rather has a new flow direction decided jointly by the inertia itself and the gas flow, which is called the "following performance" of solid particle; the greater the granular mass, the poorer the following performance is, which causes the solid particle to impact on the pipe wall at the sharp turning point of flow field and thus results in erosion [12]. This principle was used to analyze the flow field at the **6″** T-joint of the RCD (Fig. 18), showing that the irrational structure of the 6″ T-joint made it be exposed to severe erosion in the long period of normal drilling; when the high velocity and high-concentration sand particle swarm from rock burst arrived at the wellhead, the erosion at this point was aggravated. The eroded part became very thin but had not yet been completely pierced; when the pressure in the wellbore increased, the weakest point resulted from erosion could no longer withstand the high pressure and was pierced in a burst mode; the "everted perforation edge" photo in Fig. 8 is the evidence of burst at a high pressure, and the interview record that "piercing sound was heard at wellsite, below the drill floor dusts were observed" is the direct proof of piercement.

4.7. Speculation about "blockage of the first 9″ T-joint with a cecum-end on blooie pipe and increase of wellbore pressure"

According to the gas and solid two-phase flow theory, when the flow field direction suddenly changes, the solid particles impact the pipe wall and reflect, and then are moved by the gas flow at a higher speed once more. When the solid particles are very sparse, there is no apparent interference action among them; but when the solid particles are very dense, the mutual interference action among them would seriously affect their remigration, or they are even accumulated [12]. The first 9″ T-joint with a cecum-end on blooie pipe is shown in Fig. 19a, and the flow field analysis on it is shown in Fig. 19b; it is discovered based on an analysis that the structure of the first 9″



a. The T-joint b. Piercement of the T-joint

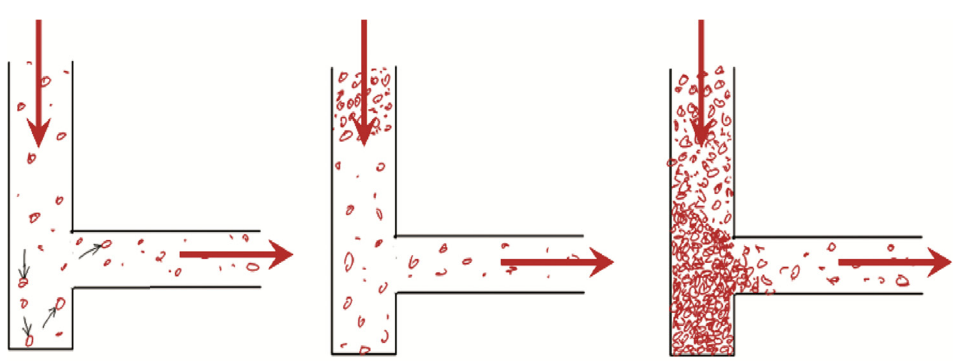
Fig. 18. Simulation of a flow field at the 6″ T-joint of the RCD.

a. A real 9″ T-joint with a cecum-end b. Flow field modeling of a T-joint bune cap

Fig. 19. The first 9″ T-joint with a cecum-end on the blooie pipe.

T-joint with a cecum-end cannot allow a sudden large stream of clasts to be duly discharged at the time of rock burst: in normal drilling, sparse solids flow can ensure the clasts to successfully pass through, but would result in blockage when a large stream of settled sand approaches. Actually, there was a case similar to the blockage of a T-joint bune cap on blooie pipe in the past: in 2008, when gas drilling was conducted in Well Lianhua 1 in the western Sichuan Basin, just after the bit was drilled out of the casing shoe, due to the sudden unblocking of the wellbore, lots of settled sand in the borehole intensively arrived at the blooie pipe, and resulted in blockage at the bune cap of the first ground T-joint. The blocking process of T-joint bune cap is sketched in Fig. 20.

The local blockage at the first 9″ T-joint with a cecum-end results in the increase of pressure in the blooie pipe in front of the blockage spot and in the wellbore; the more serious the blockage, the sooner and greater the pressure rises. Based on 1×10^6 m^3/d gas flow rate, a flowing wellbore computation model of gas drilling [13] was used to conduct calculation, with the calculation results shown in Fig. 21. Observed from



a. Sparse phase particle swarm b. Arrival of dense-phase particle swarm c. Blockage of the bune cap

Fig. 20. Sketch of settled sand blockage in the first 9″ T-joint with a cecum-end.

the Figure, when the degree of bridging of the blockage spot is smaller than 60%, the pressure in the wellbore rises slowly and not obviously; when it is larger than 60%, the pressure starts to rise obviously; when it is larger than 80%, the pressure rises sharply; when it exceeds 83%, the wellhead pressure can be increased to be more than 10 MPa.

The 6″ T-joint at the outlet of RCD also has a bune cap, but why does the blockage not occur here, but instead in the first 9″ T-joint on the blooie pipe? It is noted that as for The 6″ T-joint at the outlet of RCD, its discharge port connected with the wired hose is basically straight downwards, where although there is also mutual collision and accumulation trend when substantial clasts arrive, the downward outlet makes the clasts hard to accumulate due to the action of gravity, which makes the clasts easier to slide into the downgoing wired hose. However, the case is quite different in the first 9″ T-joint on blooie pipe, where the clasts coming at high speed directly impact the blanking plate, rebound and are instantly obstructed by the subsequently rushing clasts; after collision, the clasts lose momentum and settle on the lower pipe wall; more and more clasts are accumulated and become tighter under pressure, and blockage is formed before long.

4.8. Speculation about the direct cause of the accident in Well Qionglai 1

The direct cause of the accident in Well Qionglai 1 seemingly lies in that the 6″ T-joint fell off the 9″ to 6″ bell joint at the side outlet of the RCD, from which a great deal of natural gas carrying rock particles was ejected at high speed, then, the high speed rock particles struck the steel frame, making sparks and triggering the deflagration of natural gas. However, what is the upper level event causing this accident? What is the root cause? It is shown by the evidence of "interview record of the accident" that piercing sound was heard, below the drill floor dust was observed, a few seconds later, a dull blare was heard, and immediately, the wellhead and drill floor were on fire. It is shown by the evidence of "post-accident investigation data" that the 6″ T-joint had fallen off the 9″ to 6″ bell joint of the RCD, and the wired hose had fallen off the 6″ T-joint. Any of the two falling-offs could result in natural gas ejection and wellsite conflagration. Then, what any of the two falling-offs is corresponded by the "one blare"? How to interpret the fact that the two falling-offs are corresponded by one blare? What are the sequence and causes of the two "falling-offs"?

4.9. Speculation about the "falling-offs of the 6″ T-joint and the wired hose"

Firstly, the falling-off of the 6″ T-joint connected the wired hose is analyzed.

Can the increase of pressure in wellbore cause the 6″ T-joint thread to slip? When the wellbore pressure reaches the maximum dynamic load-bearing pressure at the stripper rubber of the RCD (10.5 MPa), the force of it acting on the blanking plate of the 6″ T-joint is 376.8 kN, which is much less than the 750 kN anti-slippage tension of the 6″ T-joint thread. Therefore, in case the stripper rubber of the RCD does not fail, wellbore pressure increase will not cause the 6″ T-joint thread to slip.

However, if the high pressure gas in the wellbore carries substantial settled sands and rushes to the wellhead, a great impact will be exerted on the blanking plate of the 6″ T-joint [14], which will possibly slip under a great dynamic tension. When different gas flow velocities and solid concentrations of gas are given, and simple correlation computation method is used, the slip force of the settled sand thrust acting on the 6″ T-joint blanking plate will be estimated, as shown in Fig. 22. Obviously, given that the anti-slippage tension of the 6″ T-joint thread is 750 kN, if the gas flow velocity is enough high (higher than 500 m/s) and the sand particle concentration is enough large (larger than 15%), it is possible for the thrust to make the 6″ T-joint thread slip.

However, it was observed that the wired hose on the blooie pipe had already been completely broken and fallen off the 6″ T-joint; if the 6″ T-joint thread falls off, the wired hose and the 6″ T-joint connecting it would instantly release pressure and become force-free, and the wired hose would not be explosively fall off the 6″ T-joint. Therefore, the speculation about "the 6″ T-joint

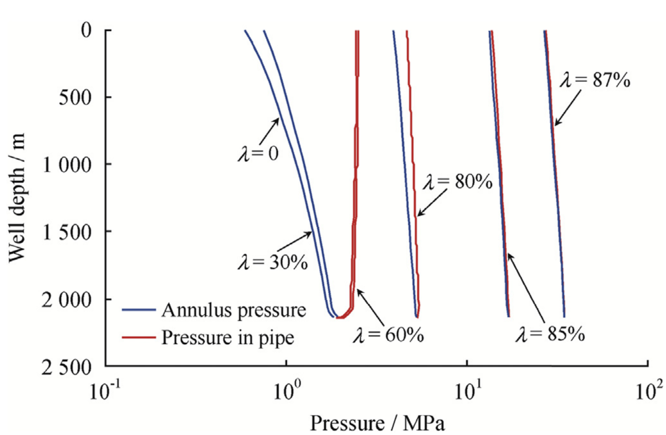


Fig. 21. Wellbore pressure increase resulted from the blockage of blooie pipe (λ: degree of bridging).

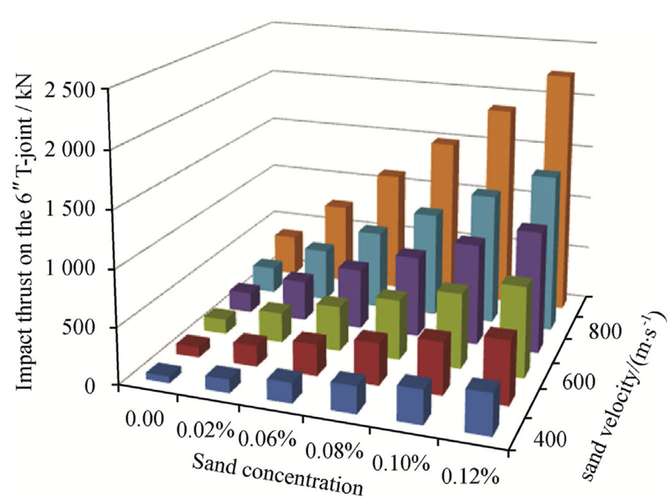


Fig. 22. Computation of thrust on the 6″ T-joint.

being thrust away by impact thrust” is inconsistent with the fact of the accident process, and the event of “falling of the 6″ T-joint off the 9″ to 6″ bell joint” would not be earlier than the event of “falling of the wired hose off the 6″ T-joint”.

As shown in Fig. 23, in the long-term normal drilling, fluid-structure coupled vibration would occur on the wired hose [15], and the alternate load of vibration could cause the wires inside the hose to suffer fatigue damage. Based on the analysis of a principal vibration mode shown in Fig. 23, the fatigue failure of the wires should occur at the swing sides of the inlet section of the wired hose, and be lighter at the side closer to the blooie pipe, whereas there is no obvious fatigue failure at both sides perpendicular to the swing. As shown by the photos in Fig. 4a and b, the fractures of most wires at both sides of the burst section are regular, characterized by fatigue fracture and brittle tensile failure, and severer at one side; whereas at two other perpendicular sides, there is no apparent fatigue failure feature. These findings indirectly prove the existence and law of fatigue damage of the wires. The fracture and damage of wires would largely reduce the bearing capacity of the wired hose from 14 MPa of a new hose to less than 10 MPa [16] (dynamic seal pressure of the stripper rubber in the RCD).

After the first 9″ T-joint on the blooie pipe was blocked, the pressure in wellbore continued to rise. As shown in Fig. 24, the rated bearing capacity of the wired hose was 14 MPa, and the dynamic seal pressure of the stripper rubber in the RCD was 10.5 MPa. In theory, excessive high wellhead pressure will not first cause the wired hose to burst, but rather outburst the stripper rubber in the RCD. Because the piercement or failure evidence of the stripper rubber in the RCD under high pressure has not been discovered, the wellhead pressure at the time of the wired hose burst should be less than 10 MPa, whereas the actual bearing capacity of the wired hose should also be less than 10 MPa due to the fatigue damage of wires. The hook load just before the moment of the wired hose burst was 635 kN, and there was still a loss of 180 kN weight in suspension. Computation shows that the upthrust acted on the drilling tool under 10 MPa pressure in the wellbore was 140 kN, and the gas flow impact force acting on the drilling tool also amounted to tens of kN. This indicates that the speculation of “the pressure in the wellbore was smaller than 10 MPa before the hose burst” is valid.

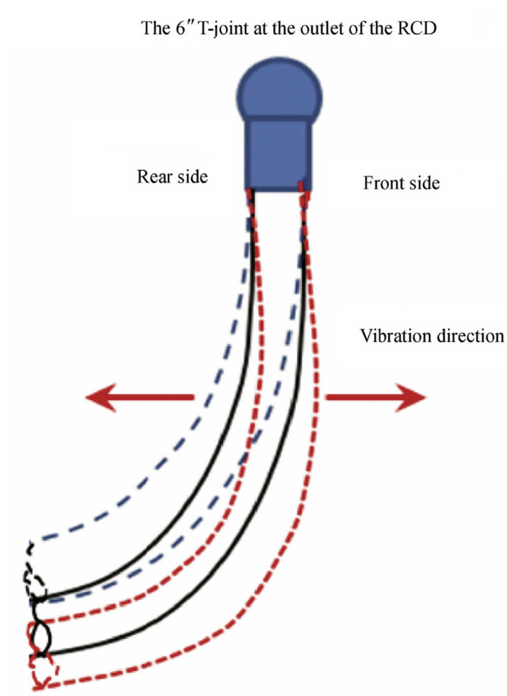


Fig. 23. Fluid-structure coupled vibration of the wired hose.

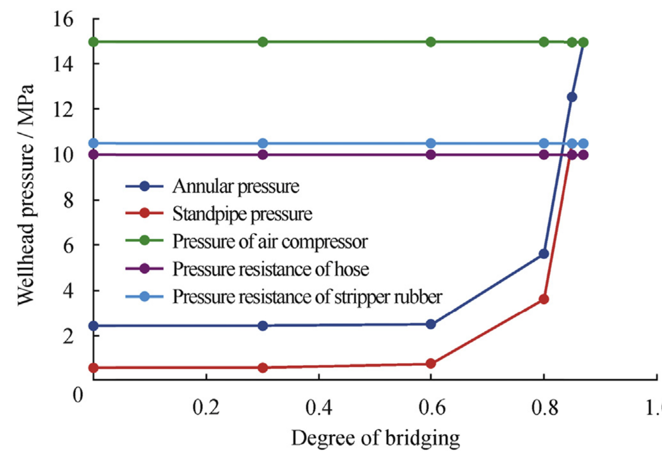


Fig. 24. Degree of bridging vs wellhead pressure.

As shown in Fig. 25, at the moment of the burst of the hose, the gas pressure energy is converted into impact energy; suppose that the pressure in the hose is 10 MPa before its burst, and the jet velocity at the moment of the hose burst will exceed acoustic velocity; suppose that the volumetric concentration of the sand particles is 4%, the gas flows out carrying the sand particles, the sudden impact counterforce at the burst point will be up to 280 kN, and this makes the 6″ T-joint thread suffer very large impact bending moment; the action direction of the bending moment is roughly from bottom to top, with an inclination of about 30° (shown in Fig. 25); and this impact bending moment results in the asymmetric deformation of the thread in this direction (photo in Fig. 3).

Under the coaction of this impact bending moment and the pressure in the wellbore, the 6″ T-joint thread of the wired hose elastically slipped from the 9″ to 6″ bell joint. Therefore, the correct speculation should be that the wired hose burst first, in the meantime, the recoil of the hose burst and the impact force in the wellbore jointly acted to make the 6″ T-joint thread elastically slip from the 9″ to 6″ bell joint, and the “one blare” corresponded to the simultaneously-occurred “the wired hose burst” and “the 6″ T-joint slip”.

As shown in Fig. 26, after the 6″ T-joint was separated from the 9″ to 6″ bell joint, the unbroken wires below the burst fracture of the wired hose still connected the hose to the 6″ T-joint. In this way, the hose was connected to the 6″ T-joint and hanged over the workbench below the drill floor, and suffered the impact of high speed ejected gas flow. When the natural gas caught fire, under the coaction of high temperature from combustion, gravity and gas flow impact force, the wires connecting the hose to the 6″ T-

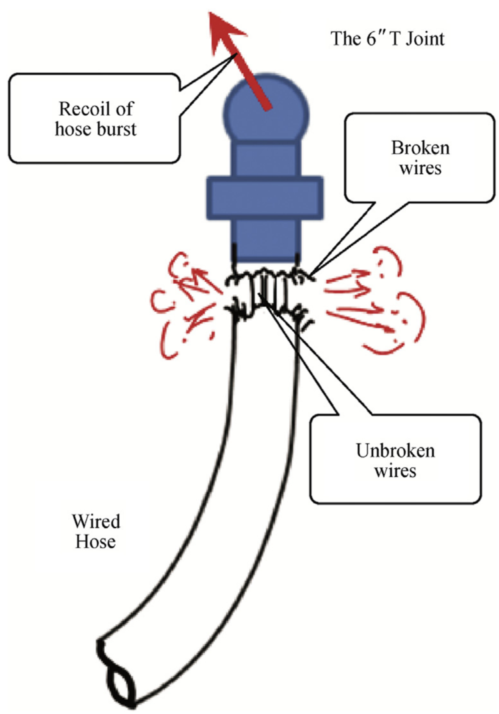


Fig. 25. Burst of the wired hose.

joint was softened by high temperature, lengthened and finally broken; then, the gas flow pushed the 6″ T-joint to fly to the lower part of the drill floor, whereas the hose slid down on the ground. As shown by the photo in Fig. 4b, the fine-drawn, lengthened and pinpoint-tipped wires show the characteristics of tensile failure deformation at high temperature from combustion under stress circumstances.

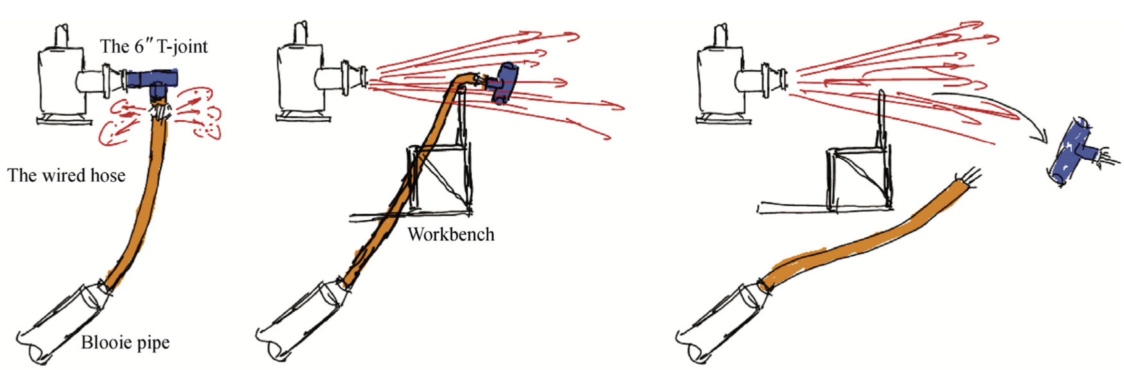
Is it possible for the impact force of a large stream of high-concentration solids and gas flow flowing through the wired hose to "pull apart" the hose? If the speculation that "there is bridging-off in the first 9″ T-joint on the blooie pipe" is correct, the reason for the burst of the hose is the pressure increase in it due to the bridging-off in the blooie pipe, whereas the aforesaid analysis indeed proves that there is bridging-off in the first 9″ T-joint on the blooie pipe. The secondary proof comes from the nitrogen drilling in Well Longgang 001 in the Sichuan Basin: downhole rock burst occurred in the well in 2008, and the blooie pipe was broken. Well killing was conducted through immediate shut-in, so no subsequent accidents occurred. There was no 6″ wired hose connecting to the blooie pipe in the well, and the whole blooie pipe was composed of 9″ casing; however, there was a 9″ T-joint with a cecum-end as in Well Qionglai 1, therefore, it should be the high pressure resulted from the blockage in the 9″ T-joint with a cecum-end that made the blooie pipe burst and break.

4.10. Estimation of gas flow rate in the process of the accident

It was observed that from 03:29, the weight in suspension basically stayed constant, and was 38.74 kN less than that in normal drilling, indicating that the well had already entered a stable gas flow blowout state. Therefore, the reduction of weight in suspension can be taken as the basis for gas flow rate estimation. The factors for the reduction of the weight in suspension are as follows: the thrust of pressure in the wellbore acting on the projection section of the drill string; the impact force of gas flow on the bit, drill pipe and joint and the flow friction under wellbore circumstances; and the buoyancy of the whole drill string. In the accident, after the wired hose and the connected 6″ T-joint at the wellhead fell off, the natural gas directly flew out of the 9″ to 6″ bell joint at the side outlet of the RCD. The gas flow rate is iterated under this condition [17] (injected nitrogen volume is zero); when the outlet flow coefficient is taken as 0.92, at 1×10^6 m^3/d gas flow rate, the weight in suspension will be reduced by 38.75 kN. Therefore, the gas flow rate estimated to be 1×10^6 m^3/d at that time is creditable.

4.11. Safety risk of the blooie pipe piercement

As mentioned before, piercement occurred at the 6″ T-joint at the outlet of the RCD before the burst of the blooie pipe, but it had not brought about serious consequences. The piercement did not directly trigger the accident, just because after it, the blooie pipe explosively broke, then, the natural gas flew out of the wellbore and triggered fire. If the blooie pipe had not burst after the piercement, wellbore gas would continuously blew out of the outlet of the blooie pipe and the pierced hole of the blooie pipe; after the nitrogen in the wellbore here had blown



a. Hose burst, ejected nitrogen b. Falling-off of the 6″ T-joint, ejected natural gas c. Wires burned out, separating of the hose from the 6″ T-joint

Fig. 26. Separation of the 6″ T-joint from the RCD.

off, natural gas would continuously blowout. The natural gas blown out of the outlet of the blooie pipe would be ignited in the safe region, but the natural gas blown out of the pierced hole would permeate the drill floor and wellsite and trigger a fire before long; the high temperature of flame would burn down the rubber components like the stripper rubber in the RCD and the wired hose; in such a way, the natural gas would not blowout of the blooie pipe, but rather directly blowout of the wellhead, resulting in a bigger and continuous wellhead fire. Therefore, no matter what kind of situation it is, and whether or not rock burst occurs, the piercement of the blooie pipe is fatal.

5. Conclusions

1) In general people think that nitrogen drilling in tight gas formation is safe because the gas production is low. But a serious accident of fire blowout occurred during nitrogen drilling of Well Qionglai 1, that is beyond people's knowledge about the safety of nitrogen drilling. In order to get correct understanding for the accident, systematical studies and analyzes have been done.
2) Based on a complete check computation and a numerical simulation, the blooie pipe of the well is proved to be able to meet both the demand of the nitrogen drilling for enhancing ROP in terms of cuttings carrying and pressure resistance up to 300×10^3 m^3/d the maximum gas production circumstances; even if the gas production of formation reaches 1×10^6 m^3/d, and drilling ahead could not be conducted due to the failure of cuttings carrying from the bottomhole, the blockage and burst should not occur in the blooie pipe in the course of blow-off. So the accident does not result from high gas flow rate of formation.
3) Although the blooie pipe of the well can meet the cuttings carrying and pressure resistance demand of the nitrogen drilling for enhancing ROP, there is a severe erosion problem, which results in piercement and then the leakage of natural gas, and this should be a significant potential safety hazard.
4) It is speculated from the accident analysis of Well Qionglai 1 that "rock burst" phenomenon exists in gas drilling: "rock burst" is a phenomenon of sudden burst of local rock mass possibly occurred in gas drilling of fractured tight sandstone gas reservoirs. Because it is the first time for this phenomenon to be discovered, there is no appropriate terminology to define it, the concepts of "rock burst" in mine field and "gas bomb" in ballistic research realm are borrowed to denominate it as "rock burst and blowout by gas bomb" in gas drilling, short for "rock burst".
5) The causes of "rock burst" are as follows: there is free natural gas with high pressure (reservoir pore pressure) in the fracture of tight sandstone gas reservoirs, whereas the pressure in the wellbore of gas drilling is very low; when the wellbore is close enough to the fracture, the rock wall between the wellbore and the fracture cannot resist the destructive force of high differential pressure, the rock wall suddenly bursts apart, the high pressure gas is suddenly released, a great deal of rock fragments are produced, and together with the high pressure gas, they are injected into the wellbore instantly, resulting in instant upthrust of drilling tools.
6) The clasts injected into the wellbore at high speed possibly form bridging-off and cause sticking of drill string in the narrowing flow channels at the bit or at the centralizer, and the sand bridge could be rapidly filled, compacted and thus becomes tight. The tight sand bridge separates the wellbore into two pressure systems: low pressure above it and high pressure below it. Under the action of drilling tool lifting and rotation, the bridging-off could be destructed; at the time of sand bridge destruction, the high pressure gas below it would make the sand bridge clasts be ejected upward at a very high speed, and the sand bridge clasts moved upward possibly could form another bridging-off in the narrowing point of the flow channel. Therefore, the bridging-off could be repeatedly formed and destructed.
7) Although the blooie pipe with T-joints with a cecum-end could meet the cuttings-carrying and pressure resistance demand of the nitrogen drilling for enhancing ROP, blockage would be formed at T-joints with a cecum-end under rock burst circumstances; as a result, the blockage would cause the pressure in the blooie pipe and the wellbore to increase, and thus result in the burst of stripper rubber in the RCD or of the blooie pipe.
8) The superficial reason for the accident in Well Qionglai 1 seems that the 6″ outlet T-joint fell off the 9″ to 6″ bell joint on RCD, the gas in wellbore blew out below the drill floor and triggered deflagration; but in reality, the 6″ T-joint falling-off resulted from the hose burst (both occurred almost simultaneously), whereas the hose burst resulted from the blockage in the blooie pipe.

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References

[1] Appendix D: IADC well classification system for underbalanced operations and managed drilling. In: Rehm B, Schubert J, Haghshenas A, Paknejad AS, Hughes J, editors. Managed pressure drilling. Amsterdam: Elsevier; 2005. p. 305–8.

[2] Zhao Yerong, Meng Yingfeng, Lei Tong, Tang Gui, Zhang Hanlin. The theory and practice of gas drilling. Beijing: Petroleum Industry Press; 2007.
[3] Liu Hongzhi, Gu Aimin, Liu Kezhong, Hua Yupeng, Lin Yong, Zhang Lirong, et al. Be cautious for the new safety risk induced from new technology of petroleum exploration: take QL1 well's blowout as an example. West-China Explor Eng 2013;(5):182−3.
[4] Tang Dahai, Chen Hongbin, Xie Jirong, Luo Yuanping, Cao Shichang. Reservoir forming conditions of Jurassic Shaximiao Formation, West Sichuan Basin. Nat Gas Explor Dev 2005;28(3):14−9.
[5] Gu Siman, Meng Yingfeng, Li Gao, Luo Chengbo, Li Pan. Experimental research of tight sand core flowing coupled with stress effect in gas drilling. Fault-Block Oil Gas Field 2013;20(3):366−9.
[6] Tang Chun'an, Guo Shanyun. Theory and application of rock crushing and tunnels underground engineering. Dalian: Dalian University of Technology Press; 2007.
[7] Zhang Guohua, Sun Qicheng, Huang Fangfang, Jin Feng. Jamming phenomena of a two-dimensional frictional granular system under isotropic confining. Acta Phys Sin 2011;60(12):124502.
[8] Chernigovskie AA. Directional pinpoint blasting. Beijing: China Architecture & Building Press; 1983.
[9] Wang Jingui. Principles and techniques of gas gun. Beijing: National Defense Industry Press; 2001.
[10] Zhao Xinsheng, Shu Jingrong. Theory and application of ballistics calculation. Beijing: Weapon Industry Press; 2006.
[11] Cen Kefa, Fan Jianren. Theory and simulation of gas−solid multi-phase flow in engineering. Hangzhou: Zhejiang University Press; 1990.
[12] Lian Zhanghua, Lin Tiejun, Meng Yingfeng. Basic theory and application of gas drilling. Beijing: Petroleum Industry Press; 2012.
[13] Meng Yingfeng, Lian Zhanghua, Liang Hong, Li Yongjie, Wu Shirong, Wu Xianzhu, et al. CFD numerical simulation research on cuttings-transportation in gas horizontal drilling. Nat Gas Ind 2005;25(7):50−2.
[14] Rao Jiang, Ge Manchu, Xu Jianzhong, Yang Naishuang, Mao Jinru, Gong Wuqi, et al. Experimental investigation on interaction between solid particles and wall surface. J Eng Thermophys 2003;24(1):134−6.
[15] Li Yanhua, Liu Gongmin, Ma Jun. Research on fluid-structure interaction in fluid-filled pipe. J Vib Shock 2010;29(6):50−3.
[16] Luo Xianguang, Li Chuanguang. Calculation formula of the withstand strength of wire-netted colloidal pipe. China Rubber Ind 1995;42(9):543−4.
[17] Meng Yingfeng, Li Gao. Theory and practice of underbalanced drilling for complex oil and gas reservoirs. Beijing: Science Press; 2015.